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WAS THE COSMIC WEB OF PROTOGALACTIC MATERIAL PERMEATED BY LOBES OF RADIO GALAXIES DURING THE QUASAR ERA?

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ABSTRACT

Evidence for extended active lifetimes ($> 10^8$ yr) for radio galaxies implies that many large radio lobes were produced during the "quasar era", $1.5 < z < 3$, when the comoving density of radio sources was 2 – 3 dex higher than the present level. However, inverse Compton losses against the intense microwave background substantially reduce the ages and numbers of sources that are detected in flux-limited surveys. The realization that the galaxy forming material in those epochs was concentrated in filaments occupying a small fraction of the total volume then leads to the conclusion that radio lobes permeated much of the volume occupied by the protogalactic material during that era. The sustained overpressure in these extended lobes is likely to have played an important role in triggering the high inferred rate of galaxy formation at $z > 1.5$ and in the magnetization of the cosmic network of filaments.

Subject headings: cosmology: large scale structure of universe — galaxies: active — galaxies: formation — galaxies: jets — galaxies: starbursts — radio continuum: galaxies

1. INTRODUCTION

Studies of flux density limited samples of radio sources have revealed that the comoving space densities of powerful radio galaxies declined between two and three orders of magnitude from redshifts of 2–3 to the present epoch (Dunlop & Peacock 1990; Jackson & Wall 1999; Jarvis & Rawlings 2000; Rawlings 2001; Willott et al. 2001). The star formation rate as deduced from near-infrared and optical surveys rises with cosmic epoch in a still poorly determined fashion (e.g. Steidel et al. 1999) until $z \sim 2$, and subsequently begins to decline at $z < 1-2$ (Connolly et al. 1997; Madau, Pozzetti & Dickinson 1998; Cowie, Songaila & Barger 1999). However, recent studies indicate that the peak of comoving sub-mm derived luminosity density occurred at $z \sim 2-5$ and was considerably greater than that inferred from optical surveys, which are probably affected by dust obscuration (e.g. Blain et al. 1999; Archibald et al. 2001). In view of these similar trends, it is of great interest to examine any possible links between these evolutionary patterns. Several authors have studied the role of active galaxies in compressing intergalactic clouds by their expanding radio jets or lobes, which could trigger large-scale star formation in the circumgalactic material (e.g. Begelman & Cioffi 1989; De Young 1989; Rees 1989; Chokshi 1997). A common perception is that despite the strong cosmological evolution of the number density of radio galaxies they fill only a minute fraction of the volume of the high-z universe. In this *Letter* we point out that the volume filling factor of the lobes of radio galaxies may well have been grossly underestimated.

The role of inverse Compton (IC) losses due to the cosmic microwave background radiation (CMBR) in limiting the observed life spans of high-z radio galaxies has been emphasized recently by Blundell & Rawlings (1999) and Blundell, Rawlings & Willott (1999, hereafter BRW99) although it has been considered in earlier studies (e.g. Rees & Setti 1968; Gopal-Krishna, Wiita & Saripalli 1989; Kaiser, Dennett-Thorpe & Alexander 1997). Thanks to both adiabatic and IC losses, a significant fraction of sources, both intrinsically weak ones, as well as the older, and hence, most expanded, intrinsically powerful ones, would be rendered undetectable in flux limited surveys for much of their active lifetimes (§2.1). In addition, the redshift interval over which radio galaxies were much more abundant, centered around $z \simeq 2.5$, the so-called "quasar era", lasted long enough to encompass several generations of radio active galaxies (e.g. Jarvis & Rawlings 2000; Barger et al. 2001) (§2.2).

The intense galaxy formation activity during that era was confined to the sheets and filaments containing higher density baryonic material, much in the form of the warm-hot medium (with temperatures of 10^{5-7}K). As indicated by recent simulations (Cen & Ostriker 1999) such filamentary structures probably occupied only a tiny fraction ($\eta \sim 0.03$) of the universe at $z \simeq 2.5$. By that time, most galaxies already formed, along with much circumgalactic material, would be located at the junctions of the filaments (Bryan & Norman 1998; Davé et al. 2001) (§2.3).

Although none of the above factors are precisely known, we argue that reasonable estimates for all of them can be obtained, and thus infer that much of the filamentary structure containing the protogalactic medium was directly impacted by the expanding overpressured lobes of radio galaxies born during the quasar era (§3). Their role

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in triggering the dramatic star formation activity seen at $z \sim$ 1–2 should therefore be closely examined.

2. THE VOLUME ENCOMPASSED BY RADIO LOBES

2.1. *The truncated visibility of high-z sources*

As highlighted by BRW99, the depletion of energetic particles due to adiabatic and enhanced IC losses at high-z can lead to a "youth-redshift degeneracy" (Blundell & Rawlings 1999). With increasing z, radio galaxies will only be observed in progressively earlier phases in any flux limited survey. Taking a fixed lifetime T, of 5×10^8 yr for the nuclear activity, BRW99 have argued that at $z = 2.5$, a source with a fairly high beam power of 2×10^{38}W would become undetectable after only a few Myr, even in the deepest meter-wavelength (151 MHz) complete samples with redshift data. We define the fractional duration of detectability, $f_d \equiv \tau/T$, with τ the time for which the source remains above the flux density limit of the survey. It should be noted that even after falling below the detection threshold, the lobes of such a radio source will continue to grow in size.

While we have drawn upon the most recent and sophisticated models for beam dynamics, which successfully reproduces a large number of slices in the observed $[P, D, z, \alpha]$ parameter space, the poor understanding of the high-z circumgalactic medium introduces uncertainties, as does the neutral assumption of a redshift independent active lifetime, T. In the BRW99 model, the total length of the source, $D(t)$, is related to the power in each beam, Q_0:

$$D(t) = 2c_1 a_0 \left(\frac{t^3 Q_0}{a_0^5 \rho_0}\right)^{1/(5-\beta)}. \qquad (1)$$

The ambient density profile is $\rho_{\rm ext}(r) = \rho_0 (r/a_0)^{-\beta}$, with reasonable values being $\rho_0 = 1.67 \times 10^{-23}$kg m^{-3}, $a_0 =$ 10 kpc, $\beta = 1.5$, and $c_1 = 1.8$. In the absence of a consensus on the cosmological evolution of these parameters, we follow BRW99 in making the neutral assumption that a_0, β, ρ_0 and T are independent of z; however, we allow for $1 \leq T/10^8$y ≤ 5. Here we consider cosmologies with $H_0 = 50$ km s^{-1}Mpc^{-1}, $\Omega_{\rm M} = 0$ or 1, and $\Omega_\Lambda = 0$.

2.2. *Radio luminosity function (RLF)*

The most recent determination of the cosmological evolution of the RLF is based on three flux-limited samples derived from surveys at low radio frequencies (151/178 MHz), the 7CRS, 6CE, and 3CRR, which are complete above the flux density limits ranging from $0.5 - 12$ Jy at 151 MHz (Willott et al. 2001). Spectroscopic redshifts obtained for 96% of the total of 357 sources in these samples provide an unprecedented coverage of the $P - z$ plane, and thereby can resolve substantially the degeneracy between luminosity, P, and z. The selection at low frequencies minimizes the orientation bias due to relativistic beaming and hence the morphological diversity of sources.

Note that the derived RLFs only reflect the sources that are visible above the 0.5 Jy limit of the deepest sample, so the computed durations of the visible phase at 151 MHz in the BRW99 model at can be directly applied to these RLFs in a self-consistent manner. The very rapid cosmological evolution of the more powerful sources, of Fanaroff-Riley (1974, FR) Type II, with $P_{151} \geq 10^{25.5}$W Hz^{-1}sr^{-1} makes the RLF at $z \simeq 2.5$ essentially flat between that power and $\log P_{151} = 27$, above which the RLF declines rapidly. By $z \sim 2$, the RLF of powerful sources has risen by nearly 3 dex above the local RLF, followed by a possible slow decline at higher redshifts (Willott et al. 2001; also Jarvis & Rawlings 2000).

As our main concern is with the volume encompassed by radio lobes during the entire quasar era, we shall consider all powerful, i.e., all FR II, radio sources, whether radio galaxies or quasars. The comoving space density of FR II sources around $\log P_{151} = 25.5$ is $\rho_{\rm obs} \simeq [6.3, 3.1] \times 10^{-7}$ Mpc$^{-3}(\Delta\log P_{151})^{-1}$, where, throughout this paper, pairs of values in square brackets are for $\Omega_M = 1$ and 0, respectively (Fig. 3 of Willott et al. 2001). In order to correct these observed values of $\rho_{\rm obs}$ for the sources which have fallen below the detection limit, they should be divided by the appropriate value of f_d. The simulation results presented in BRW99 (Figs. 13 and 14) permit a conservative useful estimate of the mean of f_d at $z = 2$. A more detailed calculation is underway (Kulkarni, Gopal-Krishna & Wiita 2001). We infer that for a source to appear at all in the BRW99 dataset it must have a $Q_0 > 7.5 \times 10^{37}$W $\equiv Q_m$, where it will have $\log P_{151} = 27.0$ at an early evolutionary stage ($\tau \simeq 1$ Myr). A source with $Q_0 = 2 \times 10^{38}$W has $\tau \simeq 9$ Myr, while one with $Q_0 = 1.3 \times 10^{40}$W has $\tau \simeq 70$ Myr, so that, roughly, $\tau \propto Q_0^{0.5}$, for $Q_0 > Q_m$. Assuming a fixed lifetime for all radio galaxies, $T_5 = (T/500$ Myr) (cf. BRW99), a source will continue to expand its lobes for an extra factor of $T/\tau = f_d^{-1}$ times beyond the age at which it falls below the detection threshold of their deepest sample. Using the same probability distribution of beam powers as empirically inferred by BRW99, $p(Q)dQ_0 \propto Q_0^{-2.6}dQ_0$ for $Q_{\rm min} \equiv 5 \times 10^{37}$W $< Q_0 < 5 \times 10^{42}$W $\equiv Q_{\rm max}$ and $p(Q_0) = 0$ otherwise, we find that, normalizing to $Q_0^* = 1.3 \times 10^{40}$W, for which $f_d^* = 0.14\ T_5^{-1}$ (Fig. 13 of BRW99), $\langle f_d \rangle = 0.11 f_d^* \simeq 1.5 \times 10^{-2}\ T_5^{-1}$.

This correction factor should be applied to the observed source densities at and above the luminosity where the RLF($z = 2$) steepens, that is for $\log P_{151} \geq 26.5$ for $\Omega_{\rm M} = 1$ and $\log P_{151} \geq 27.0$ for $\Omega_{\rm M} = 0$ (see Fig. 3 of Willott et al. 2001). For the remaining FR II sources, i.e., those appearing at lower luminosities in the RLF at $z = 2$, f_d is clearly expected to be still smaller, in that such sources will have $\tau < 1$ Myr (BRW99). Furthermore, these estimates of f_d for $z = 2$ are conservative upper limits for $z = 2.5$, close to the peak of the quasar era (e.g., Rawlings 2001), and where the CMBR is even stronger.

In addition, there will be a larger population of radio sources at $z = 2.5$ which are simply not detected, because their powers are too low even at early stages, but which will also cumulatively inflate a substantial lobe volume. It is known that starburst activity can occur along the edges of even FR I radio sources (e.g., McNamara & O'Connell 1993). Maintaining our conservative approach, we shall ignore this additional contribution. Now, dividing $\rho_{\rm obs}(1+z)^3$ by the $\langle f_d \rangle$ gives the actual proper density at $z = 2.5$ of powerful radio sources born in an interval T,

$$\rho \simeq [4.1, 2.1] \times 10^{-5} (1+z)^3 T_5 \ {\rm Mpc}^{-3} (\Delta \log P_{151})^{-1} \quad (2)$$

(Willott et al. 2001). To obtain the integrated density of radio sources we consider the width of the relevant $\log P_{151}$ bin, which is about [1.25, 1.5] dex. Thus the total proper density of galaxies with beam powers sufficient to produce

FR II sources (whether or not they are detected in the survey) is $\phi(T) = [5.1, 3.1] \times 10^{-5} T_5 (1+z)^3 \mathrm{Mpc}^{-3}$.

We must finally account for the fact that the epoch during which the number density of sources is roughly constant at the above value extends from $z \simeq 1.5$ to $z \simeq 3$, with characteristic $z \simeq 2.5$ (Jarvis & Rawlings 2000; Rawlings 2001). This corresponds to a quasar era of length $t_{\rm QE} \sim 2$ Gyr which encompasses several generations of radio sources. The values of $t_{\rm QE}$ vary with Ω_M so as to compensate for the difference due to cosmology in the definition of $\rho_{\rm obs}$, so we finally find that the total proper density, Φ, of intrinsically powerful radio sources is essentially independent of T (as long as it exceeds $\sim 10^8$ yr) and Ω_M: $\Phi = \phi(T)(t_{\rm QE}/T) = 7.7 \times 10^{-3}$ Mpc^{-3}.

2.3. *Relevant volume filling factor of radio lobes*

Recent high-resolution hydrodynamic simulations of ΛCDM models suggest that at the present epoch roughly 70% of the baryons exist in a web of filaments as warm-hot gas and embedded galaxies and clusters, altogether occupying about 10% of the volume of the universe (Cen & Ostriker 1999; Davé et al. 2001). However, at $z \simeq 2.5$, the network of filaments occupied only around 3% of the comoving volume, and their mass content has steadily grown since that epoch from about 20%, at the expense of the surrounding warm medium (the gas cooler than $\sim 10^5$K, responsible for the Lyman-α absorption).

Since massive galaxies, the progenitors of powerful radio sources, lie near the junctions of the filaments, their radio jets and lobes are expected to directly interact with the cool circumgalactic material as well as the warm-hot and hot gas contained in the filaments. Significant amounts of star formation are triggered by the shocks and high pressure associated with the radio emitting features (§3). Thus, if a good fraction of this *relevant* volume of the universe was permeated by radio lobes in the quasar era, the lobes could play a substantial role in triggering the intense star formation activity seen in the universe at $z \sim 1-2$.

We can now examine the viability of this proposal. The effective volume of relevance here is just that of the filaments containing the galaxies and overdense protogalactic gas at $z \sim 2.5$, which is only the fraction η of the total volume. The volume occupied by the synchrotron emitting lobes of a powerful radio source (actually a lower limit to the volume encompassed by the outer bow shock) at an age t is

$$V(t, Q_0) \simeq (\pi/4) D(t, Q_0)^3 R_T^{-2}, \qquad (3)$$

where R_T, the ratio of the source's length, D, to its width, $2R$, is typically ~ 5 (e.g. Leahy & Williams 1984). By integrating equation (3), weighted by the distribution function $p(Q_0)$ (see §2.2), and using equation (1) for $D(t, Q_0)$, we compute the average volume filled by these sources at their maximum ages to be $\langle V(T) \rangle = 2.1\ T_5^{18/7}$Mpc^3.

3. DISCUSSION AND CONCLUSIONS

Putting together the results from §2, the fractional relevant volume which radio lobes born during the quasar era cumulatively cover is,

$$\zeta = \Phi\ \langle V(5 \times 10^8 \mathrm{yr}) \rangle\ (0.03/\eta)(5/R_T)^2 \simeq 0.5, \qquad (4)$$

for our canonical choice of T (BRW99). We emphasize that this filling factor is the sum of the lobe volumes created during the entire quasar era; this is relevant for estimating the domain of star formation triggered by the lobes. In contrast, only one generation of sources is considered in estimating the contribution to the energy density, u, of synchrotron plasma injected into the cosmic web by their lobes, since the left-over contribution from previous generations of lobes should be marginal, due to severe expansion losses. This leads to $u \simeq 2.7\ T Q_m \phi(T) \approx 2 \times 10^{-16}$J m^{-3} within the filaments. See Table 1 for specific values.

Thus, the main result is that, quite plausibly, a very significant fraction of the relevant volume of the universe was impinged upon by the growing radio lobes during the redshift interval when radio source production was at its peak ($z \simeq 2.5$). Radio lobes propagating through this protogalactic medium mainly encounter the hot ($T > 10^6$K), volume filling, lower density gas, but when they envelop the embedded cooler clumps ($T \sim 10^4$ K; Fall & Rees 1985), the initial bow shock compression will trigger large-scale star formation, which is sustained by the persistent overpressure from the engulfing radio cocoon. Note that the cocoon pressure is likely to be well above the equipartition estimate (Blundell & Rawlings 2000). This scenario is supported by many models, both analytical (e.g. Begelman & Cioffi 1989; Rees 1989; Daly 1990), and hydrodynamical (e.g. De Young 1989; Cioffi & Blondin 1992), and provides an explanation for the remarkable radio–optical alignment effect exhibited by high-z radio galaxies (e.g., McCarthy et al. 1987; Chambers, Miley & van Breugel 1988). Additional support for jet or lobe-induced star formation comes from the HST images of $z \sim 1$ radio galaxies (Best, Longair & Röttgering 1996), and of some radio sources at higher z (e.g. Miley et al. 1992; Bicknell et al. 2000).

It is important to check if the overpressure of the expanding lobes over the ambient medium persists throughout the active lifetime of the radio source. From BRW99 (cf. Falle 1991): $p_{\rm lobe} \propto t^{(-4-\beta)/(5-\beta)}$, but $D \propto t^{3/(5-\beta)}$, so $p_{\rm lobe} \propto D^{(-4-\beta)/3}$. The external pressure declines less rapidly, $p_{\rm ext} \propto D^{-\beta}$, so $p_{\rm lobe}/p_{\rm ext} \propto D^{(-4+2\beta)/3}$. For $\beta = 3/2$, $p_{\rm lobe}/p_{\rm ext} \propto D^{-1/3}$, while for $\beta = 1$, which might be more reasonable at large radial distances, $p_{\rm lobe}/p_{\rm ext} \propto D^{-2/3}$. For the ranges of Q_0, ρ_0 and a_0 considered here, appropriate for FR II sources, overpressures at $D = 50$ kpc will amount to factors of 10^2–10^4, corresponding to Mach numbers of 10–100 (BRW99) for the bowshock. Thus, overpressure should persist even for $D \gg 1$ Mpc, sustaining lobe expansion even after the jet activity ceases. Supersonic expansion into a two-phase circumgalactic medium will compress many of the cooler clouds, rapidly reducing the Jeans mass by factors of 10–100 and thereby triggering starbursts (Rees 1989). Even if most of the gas is in a single phase, rapid cooling behind the bow shock can trigger star formation (Daly 1990). The lobe-induced star formation would clearly be concentrated around the site of the active galaxy, thereby naturally introducing bias in the distribution of star forming sites.

Chokshi (1997) has suggested that radio sources at high redshift ($2 < z < 3$), powered by accretion of protogalactic material onto preexisting black holes, assembled their host elliptical galaxies via radio lobe induced starbursts. She argued for such an origin of the entire population of massive ellipticals seen at the present epoch. Here our focus is on quantitatively assessing if radio sources could

have made an impact on the entire star/galaxy formation process on the global scale. Keeping a conservative bias, we have only considered FR II lobes and therefore used a value for $\Phi(z = 2.5)$ which is less than a tenth of the value used by Chokshi. Inspired by recent models of radio source evolution and cosmic structure formation, we have taken into account a number of additional factors, which yield significant levels of effective volume coverage attained by radio galaxy lobes during the cosmic era of peak radio source production.

While we have focused our attention on the "quasar era" it is clear that f_d for radio galaxies at $z > 3$ would be yet smaller; hence ρ and their fractional volume coverage may not decline for $z > 3$, even if the quasar population was sparser, as deduced by Shaver et al. (1998). But the data are inadequate to rule out very slow declines at $z > 3$ (e.g., Jarvis & Rawlings 2000). Thus, even at those very early epochs, radio sources may have contributed substantially to the formation of galaxies, which have recently been discovered from IR and sub-mm surveys (e.g., Steidel et al. 1999; Blain et al. 1999; Archibald et al. 2001).

An interesting corollary of our picture is that the radio lobes could efficiently seed with magnetic field a large portion of the cosmic web (cf. Daly & Loeb 1990). From u (Table 1) we estimate an equipartition magnetic field in the filaments to be $\sim 10^{-8}$ G. This relatively strong field is in accord with the recent estimate for the cosmic web of filaments based on a more realistic interpretation of rotation measure data (Ryu, Kang & Biermann 1998).

We have ignored the relatively small overpressured radio lobes associated with the weaker, albeit more abundant, FR I sources. We have also neglected the explicit growth of three dimensional instabilities which will afflict even very powerful jets trying to propagate to Mpc distances (e.g., Hooda & Wiita 1998); however, under these circumstances the jet advance is likely to resemble the "dentist drill" scenario of Scheuer (1982), so while the hotspot emission may weaken, the lobes can continue to inflate and expand. Both of these effects would tend to further reduce the value of f_d and thereby increase our estimates for ζ. However, recurrent periods of activity in individual galaxies, even if they add up to $\sim 5 \times 10^8$ yr, should inflate smaller total volumes. These details will be explored in future work.

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Table 1
Densities, volumes and filling factors

T^{a}	Ω_M	$\langle f_d \rangle$	$\phi(T)^{a}$	$\langle V(T) \rangle^{a}$	ζ	u^{a}
100	0	0.077	6.2(−6)	0.033	0.01	5.6(−18)
100	1	0.077	1.0(−5)	0.033	0.01	9.2(−18)
300	0	0.026	1.9(−5)	0.55	0.08	5.0(−17)
300	1	0.026	3.1(−5)	0.55	0.08	8.2(−17)
500	0	0.015	3.1(−5)	2.05	0.53	1.4(−16)
500	1	0.015	5.1(−5)	2.05	0.53	2.3(−16)

[a]Units: $T(\mathrm{Myr}); \phi(T)(\mathrm{Mpc}^{-3}); \langle V(T) \rangle(\mathrm{Mpc}^{3}); u(\mathrm{Jm}^{-3})$